# FOCAS spectroscopy of the afterglow of GRB 130606A at z=5.9

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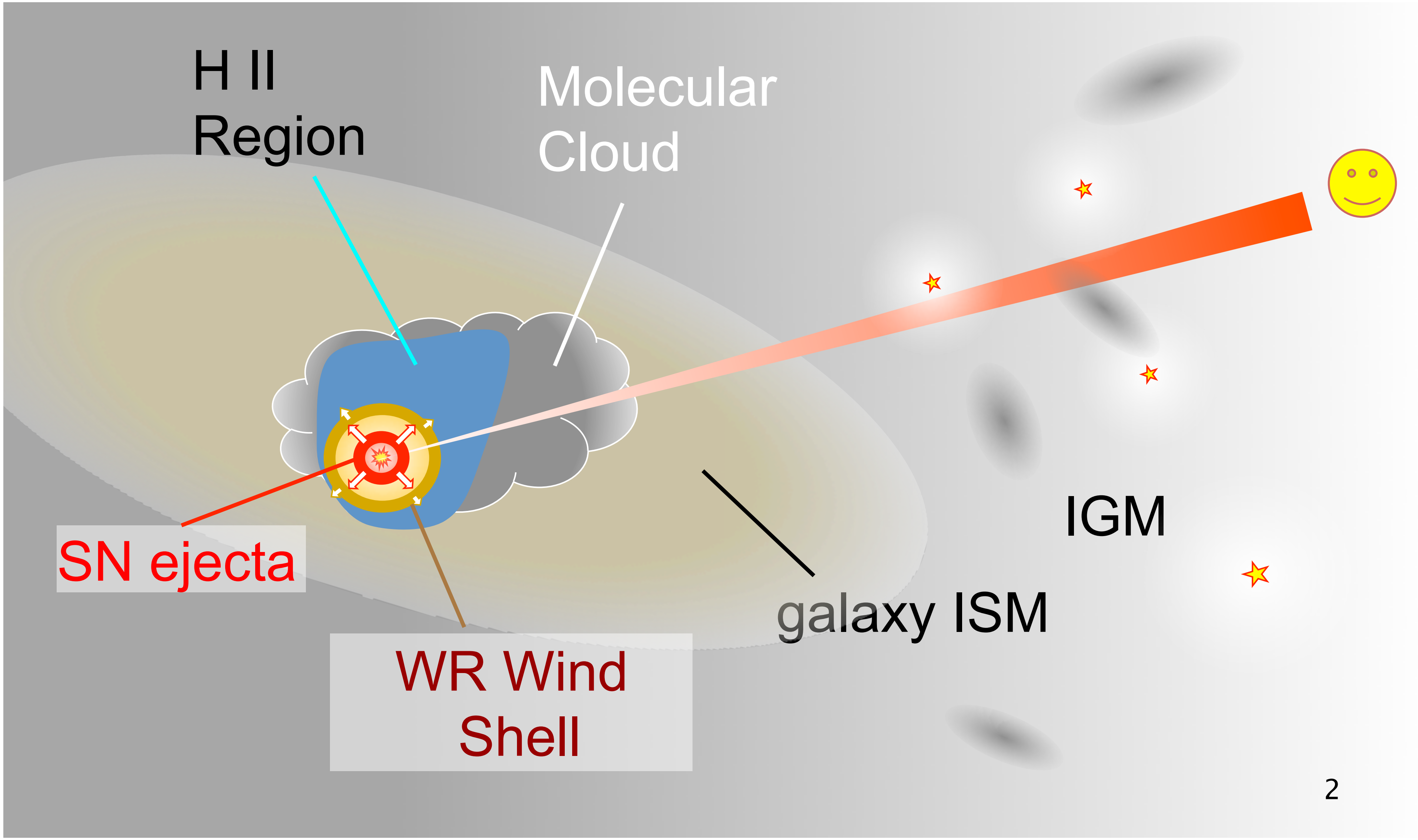
on behalf of the Subaru GRB team

arXiv:1312.3934 Totani et al.
"Probing Intergalactic Neutral Hydrogen by High Precision Analysis of the Red Damping Wing of Gamma-Ray Burst 130606A Afterglow Spectrum at z = 5.913"

# GRB Environment

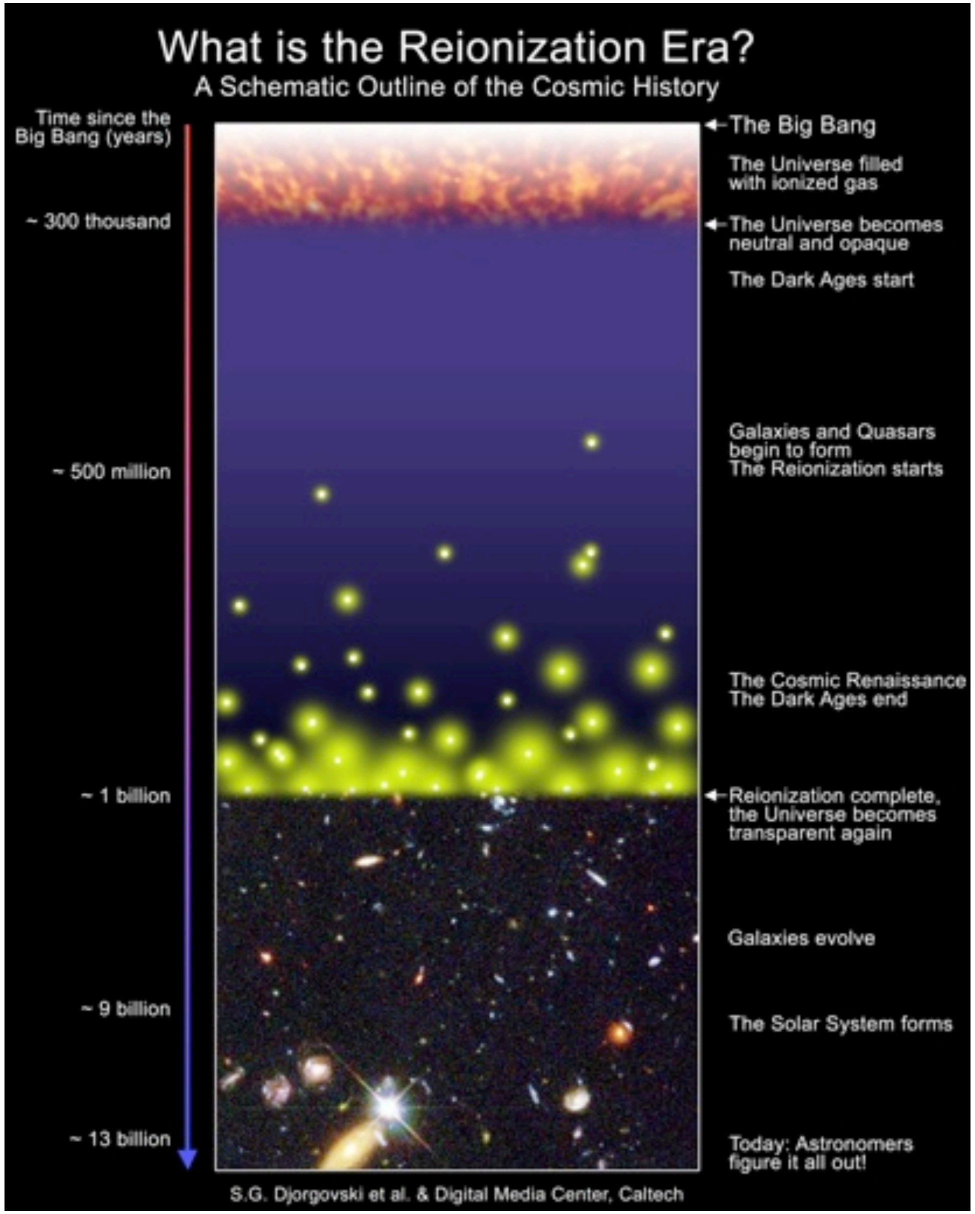


# Cosmic Reionization

- The Universe (hydrogen) became neutral at z~1100
  - the cosmic recombination
  - observed as CMB

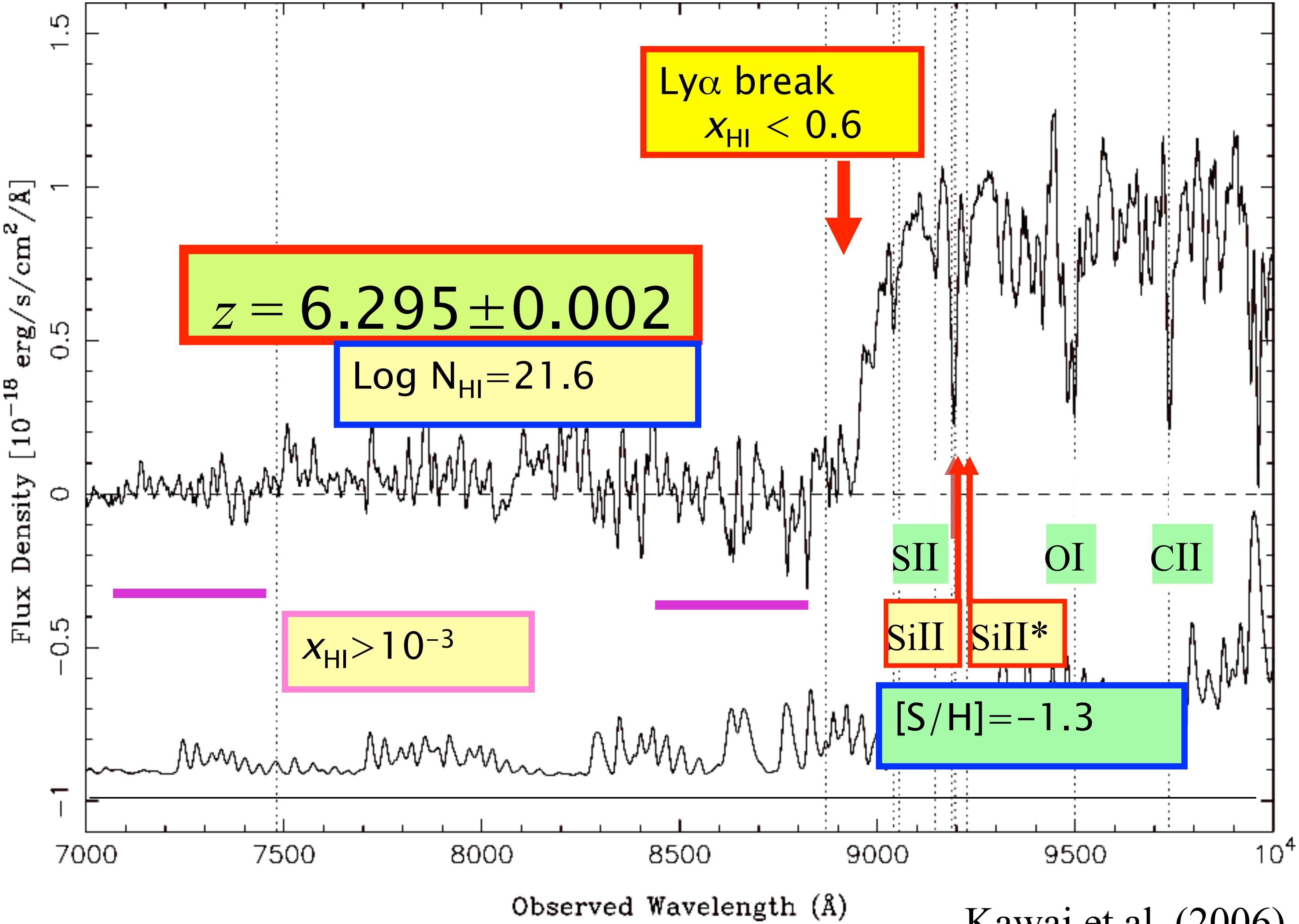
- Hydrogen in IGM today is highly ionized
  - the Gunn-Peterson Test

- The universe must have been reionized at around z~10
  - most likely by UV photons by first stars
  - when? how? important benchmark to understand galaxy formation




Djorgovski+

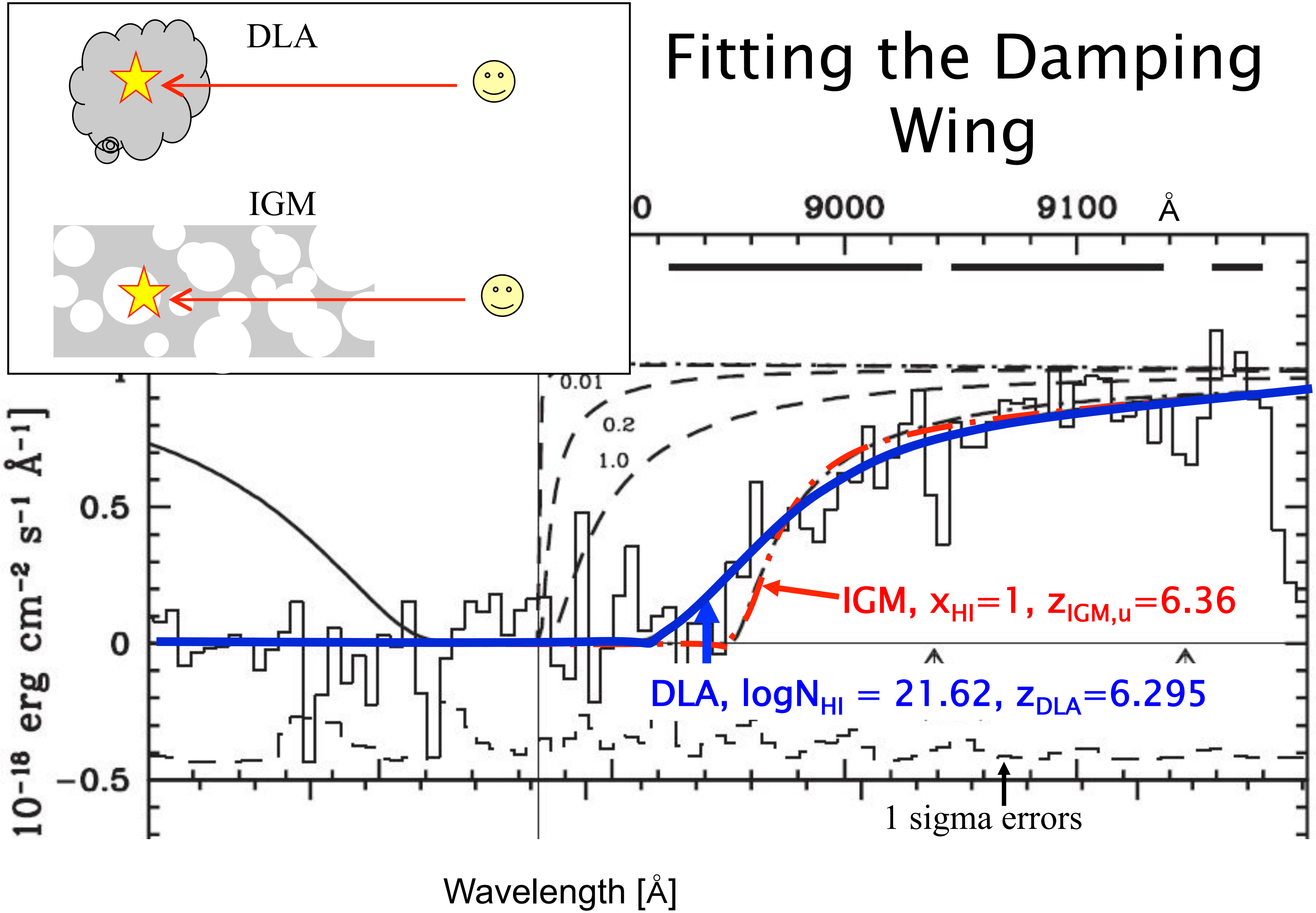
# GRB 050904 at t=3.4 d




Subaru FOCAS 4.0 hrs, $\lambda/\Delta\lambda \approx 1000$

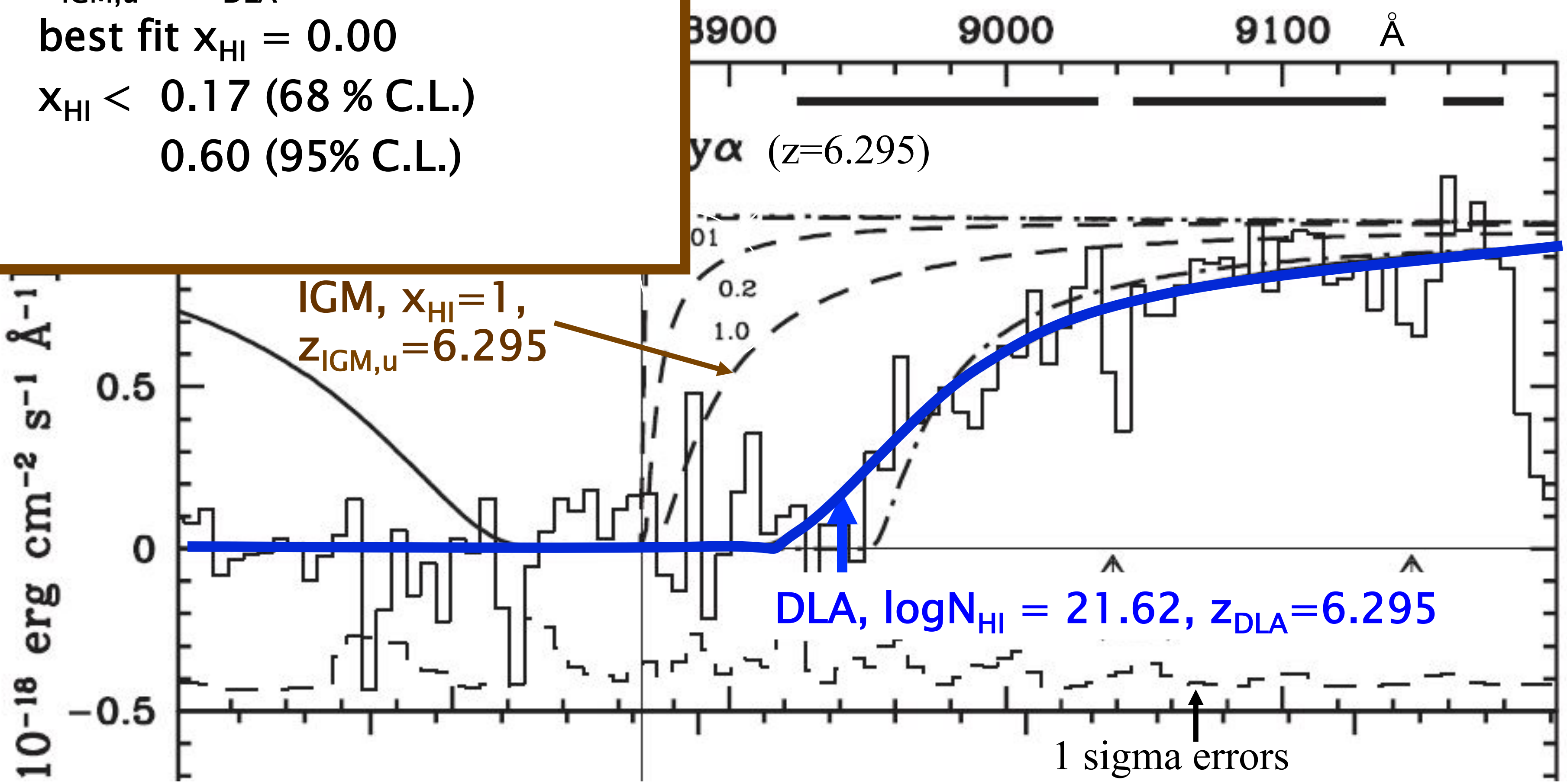
Kawai et al. (2006)
Totani et al. (2006)

# Fitting the Damping Wing



# Constraint on $x_{HI}$?

- $z_{IGM,u} = z_{DLA} = 6.295$
- best fit $x_{HI} = 0.00$
- $x_{HI} < 0.17$ (68 % C.L.)
  0.60 (95% C.L.)




Neutral IGM is not dominant in the damping wing, but it does affect the wing shape if $x_{HI} \sim 1$

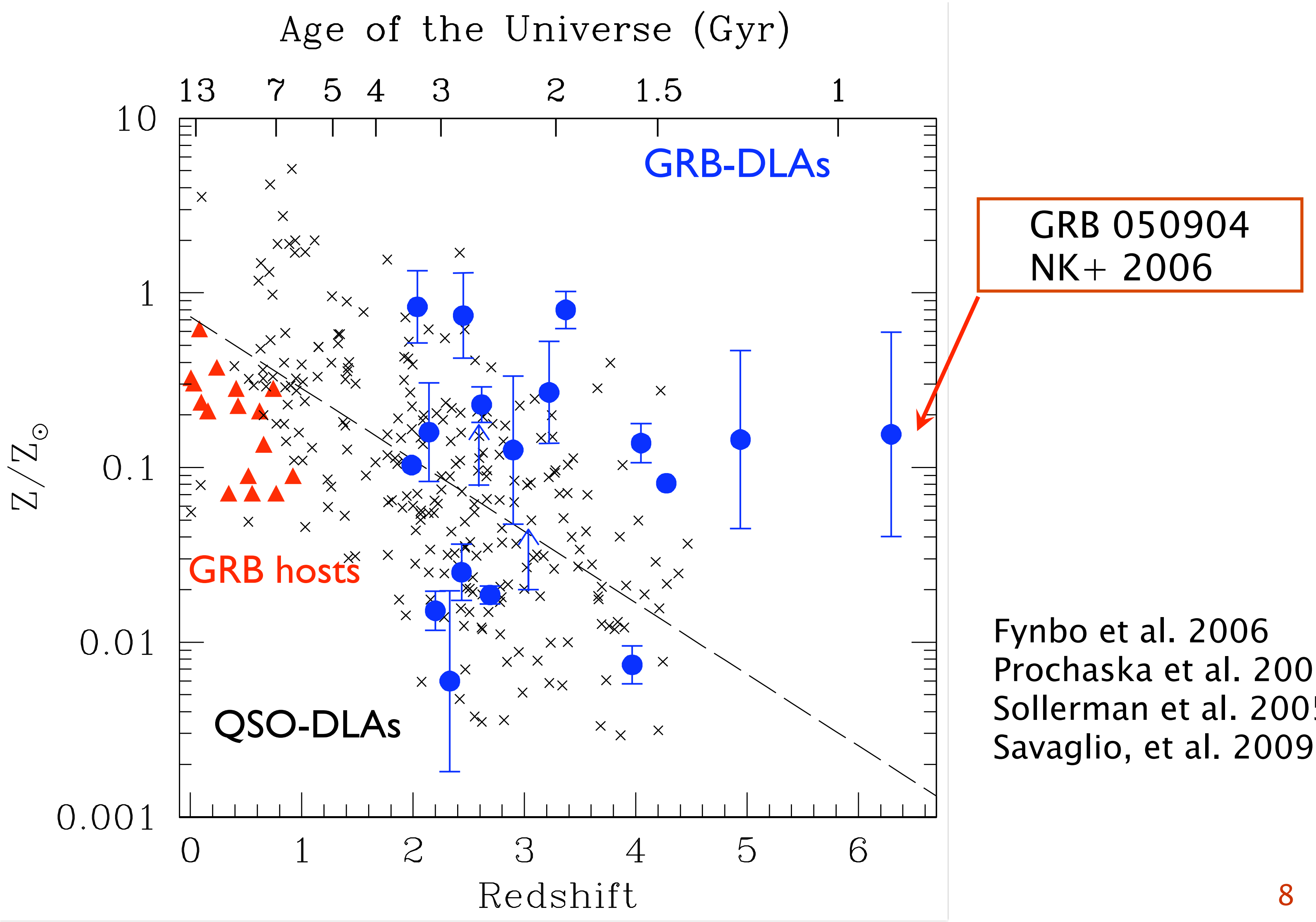
Totani et al. '06

# GRB as a Reionization Probe

- Strengths:
  - GRBs detectable at z>>6
  - probes more normal (less biased) region in the universe than quasars
    - GRBs detectable even in small dwarf galaxies
    - No proximity effect
  - Does not depend on galaxy evolution model
  - simple power-law spectrum
    - damping wing analysis to precisely measure $x_{HI}$ ($=n_{HI}/n_H$)

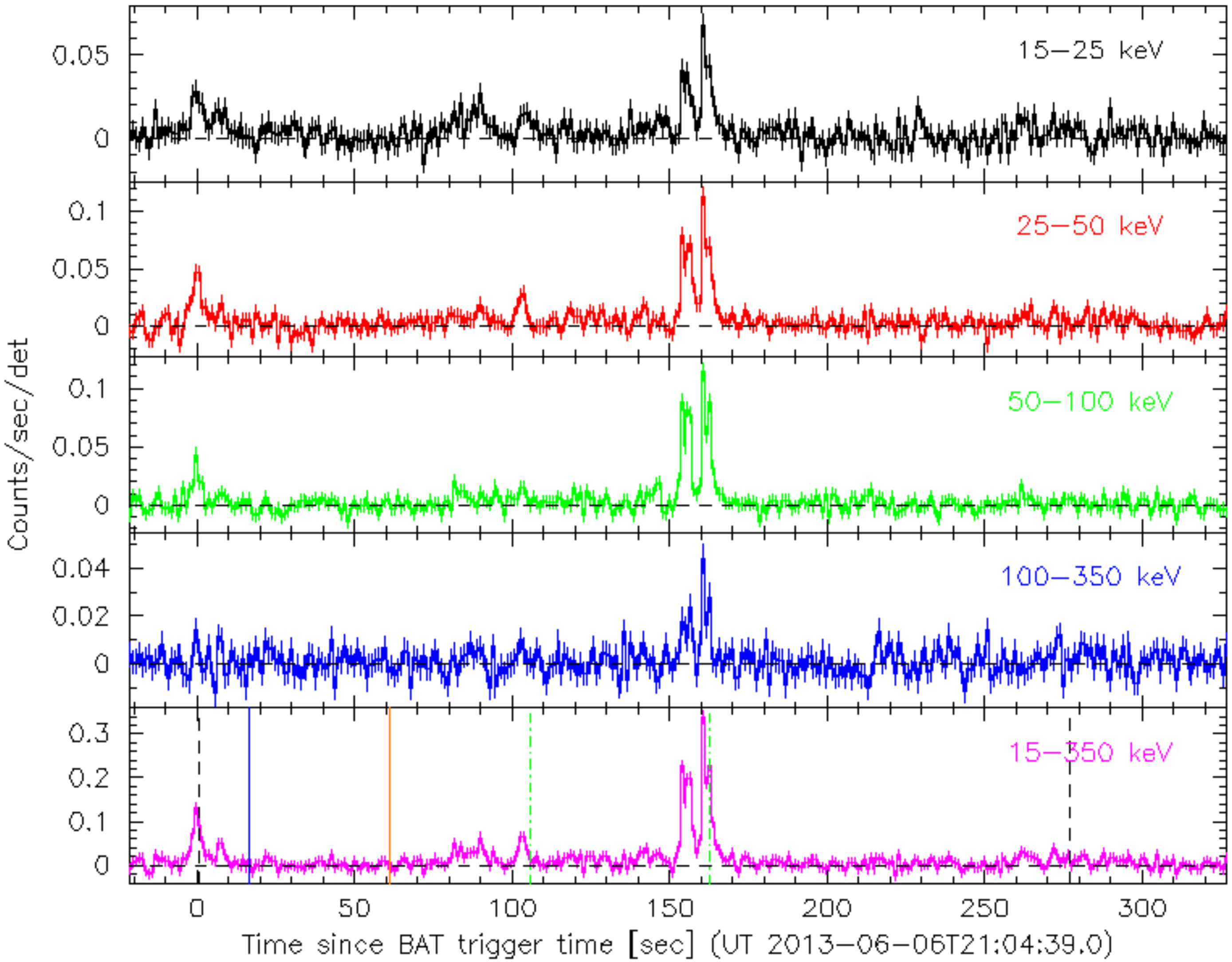
- Weakness:
  - Degeneracy in damping wing host galaxy DLA vs. IGM
    - host DLA dominant for GRB 050904
    - can be broken by metal absorption lines
    - we need low $N_{HI}$ host galaxy to measure $x_{HI}$ accurately
  - event rate not so high
    - GRB 050904 has been only one useful constraint on reionization by GRBs since 2005!
      - $x_{HI}$ < 0.17 (68%C.L) or 0.6 (95%C.L.) by fitting

# Cosmic Chemical Evolution

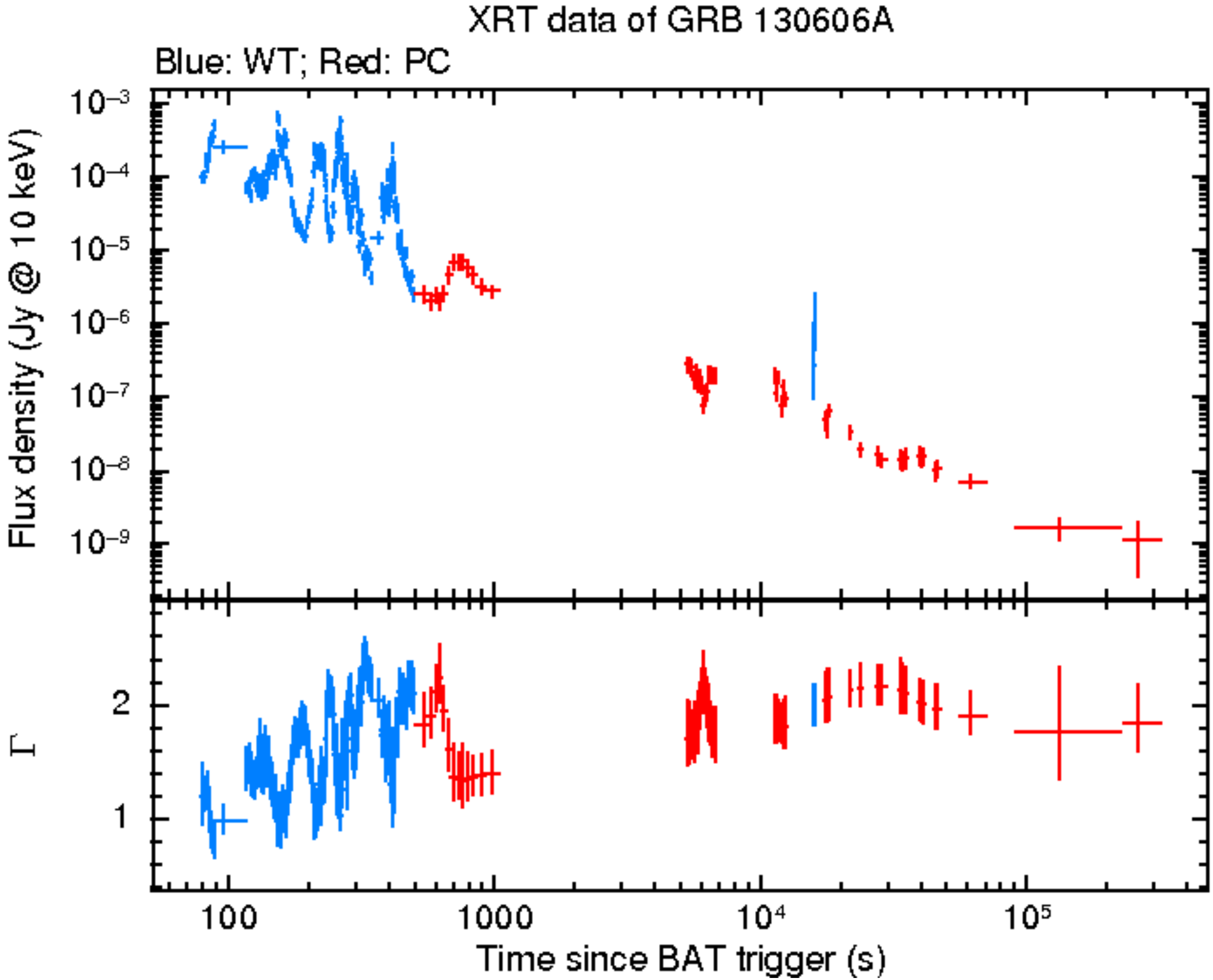



Fynbo et al. 2006
Prochaska et al. 2003
Sollerman et al. 2005
Savaglio, et al. 2009

# GRB 130606A Swift BAT




$T_{90}$=279 s

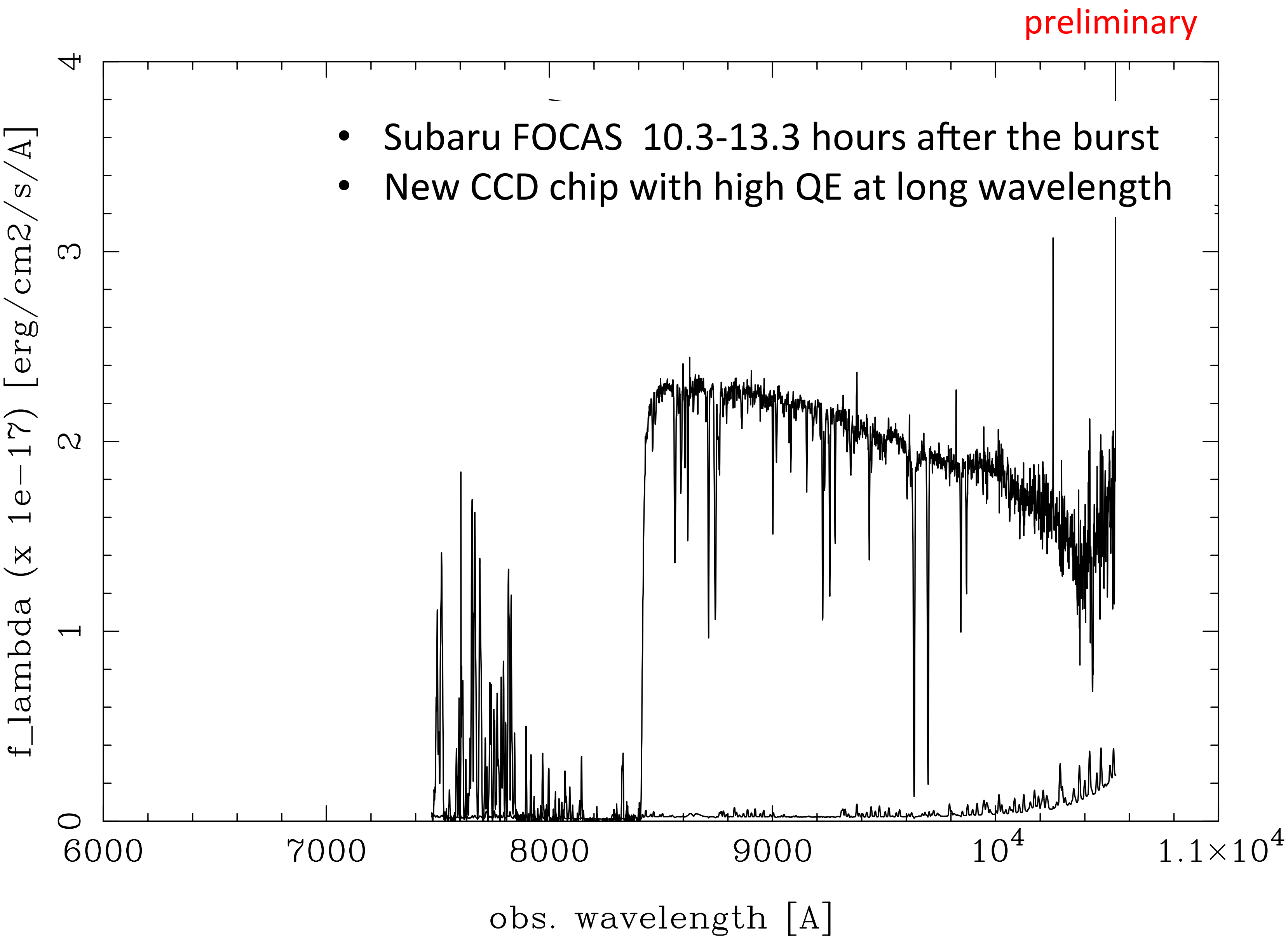


XRT data of GRB 130606A
Blue: WT; Red: PC
Flux density (Jy @ 10 keV)
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
Γ
2
1
100
1000
$10^4$
$10^5$
Time since BAT trigger (s)

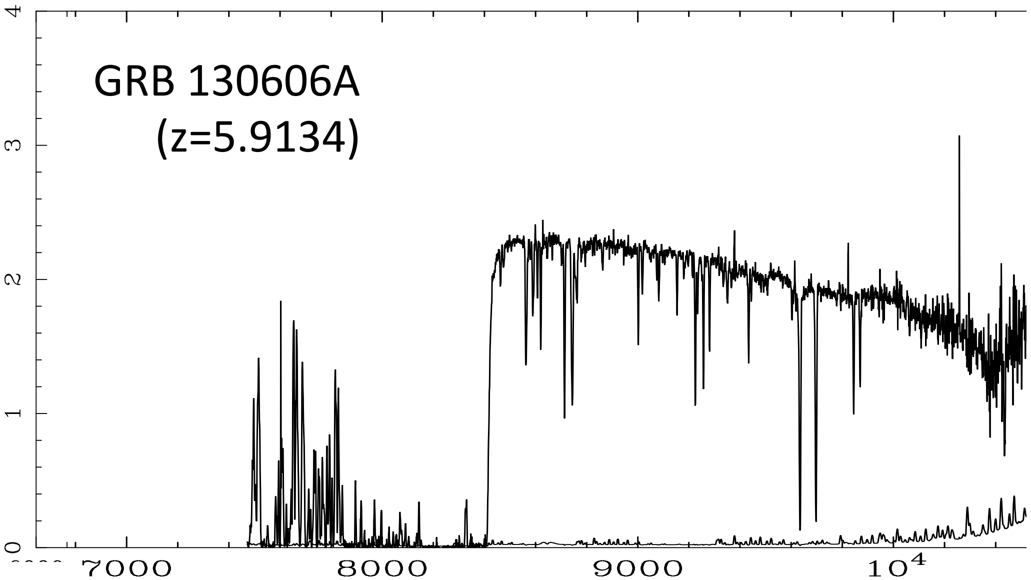
# GRB 130606A

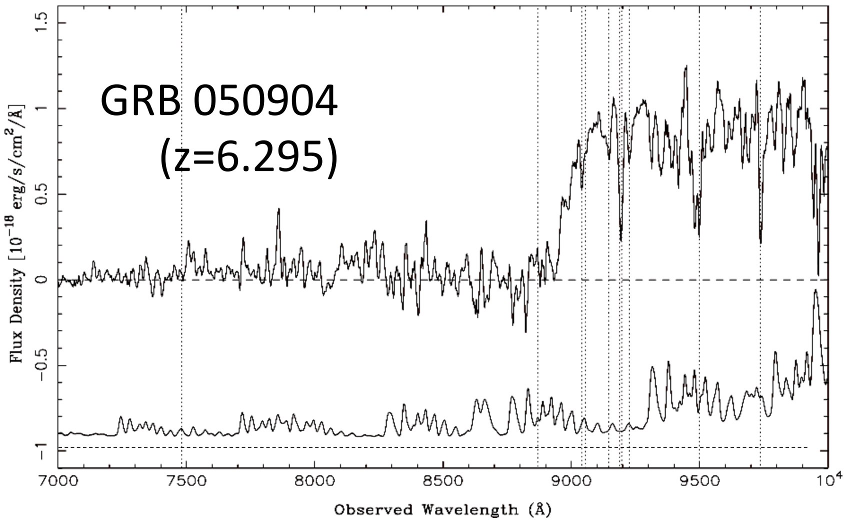
- Swift
  - Trigger 2013-06-06 21:04:39.02 UT
  - BAT position +16h 37m 37s, +29d 47' 27" (J2000)
  - Bright X-ray afterglow, no UVOT detection
- GCN
  - #14782 Jelinek et al. R=18.5 (t=21m)
  - #14783 Xu et al. r=20.8 (t=30m)
  - #14784 Nagayama J=14.7, H=13.9, Ks=13.1 (t=36m)
  - #14785 Virgili et al. i'= 18.60 (t=45m), z'=16.65 (t=48m)
  - #14790 Castro-Tirado et al. z=6.1 (break at 6500 Å)
  - #14796 Castro-Tirado et al. z=5.91 (N V, Si II, Si VI)
  - #14798 Lunnan et al. z=5.913 (N V, Si II, C II, O I)

# GRB 130606A – Subaru FOCAS



# GRB 130606A vs. GRB 050904




- $N_H \approx 7\times10^{19}$ cm$^{-2}$

→ tighter constraint on IGM

- $N_H \approx 4\times10^{21}$ cm$^{-2}$
- $x_{HI} < 0.6$ $(6.0 < z < 6.3)$

# 科研費重点領域「ガンマ線バーストで読み解く太古の宇宙」

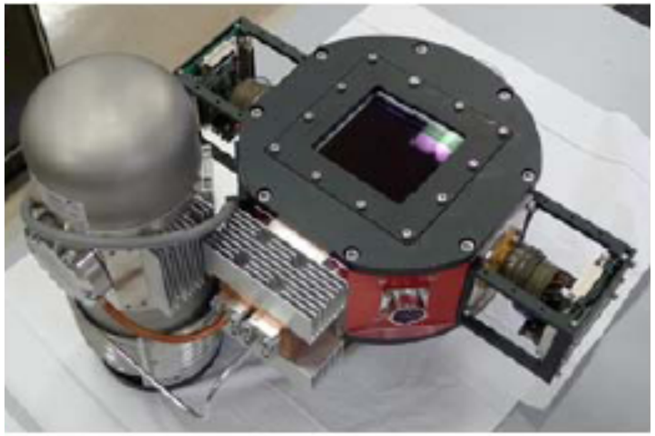
# FOCAS CCD upgrade （太田）

新CCDの導入（浜松フォトニクス）

特に0.9-1μm付近での感度が大幅向上

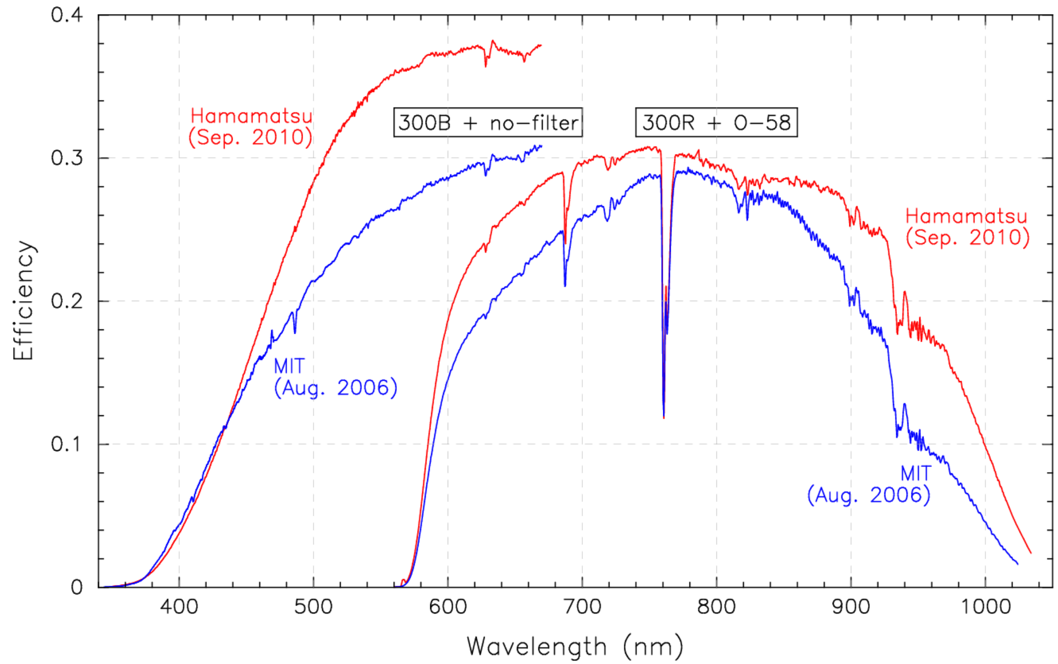
High-z天体観測に威力　0.5umで1.3倍、1.0umで2倍

他に、フリンジの減少、読出速度の向上（約4倍）、cosmetics改善



新CCDシステム

大気、望遠鏡、装置を含めた効率



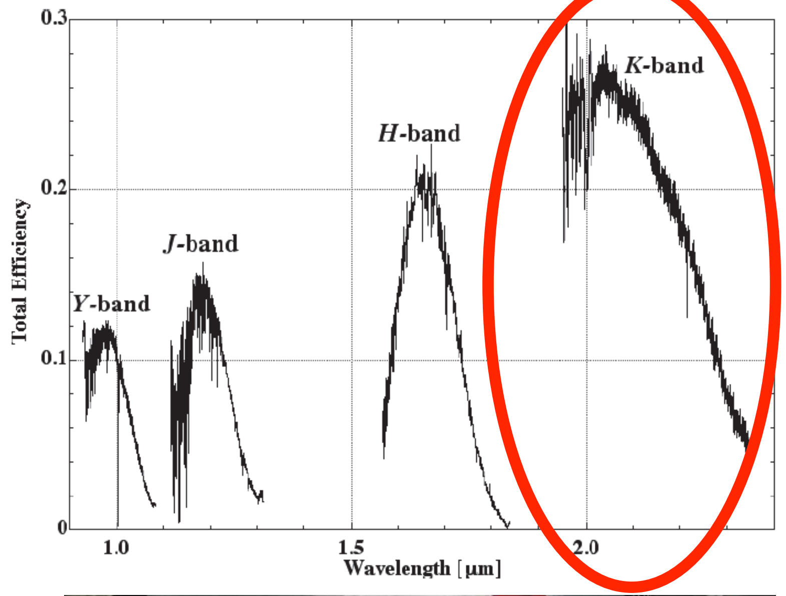

写真・図　提供：服部

Hamamatsu (new)　MIT (old)

# MOIRCSに新分散素子（VPH-K）導入　（太田）

## 高波長分解能＋高透過率

R～2680　(0.5″ slit)



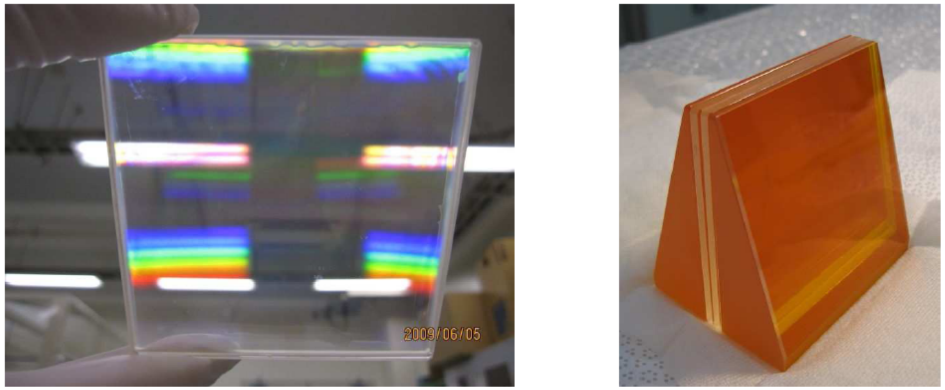
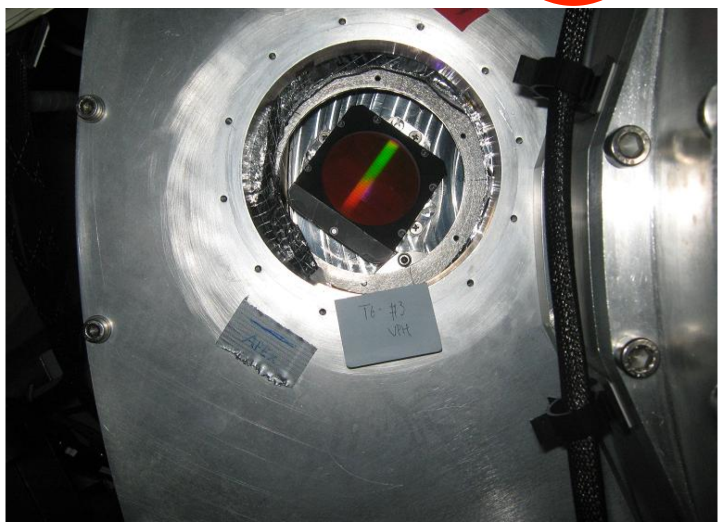




**FIGURE 1.** The grating alone (left) and completed grism (right).

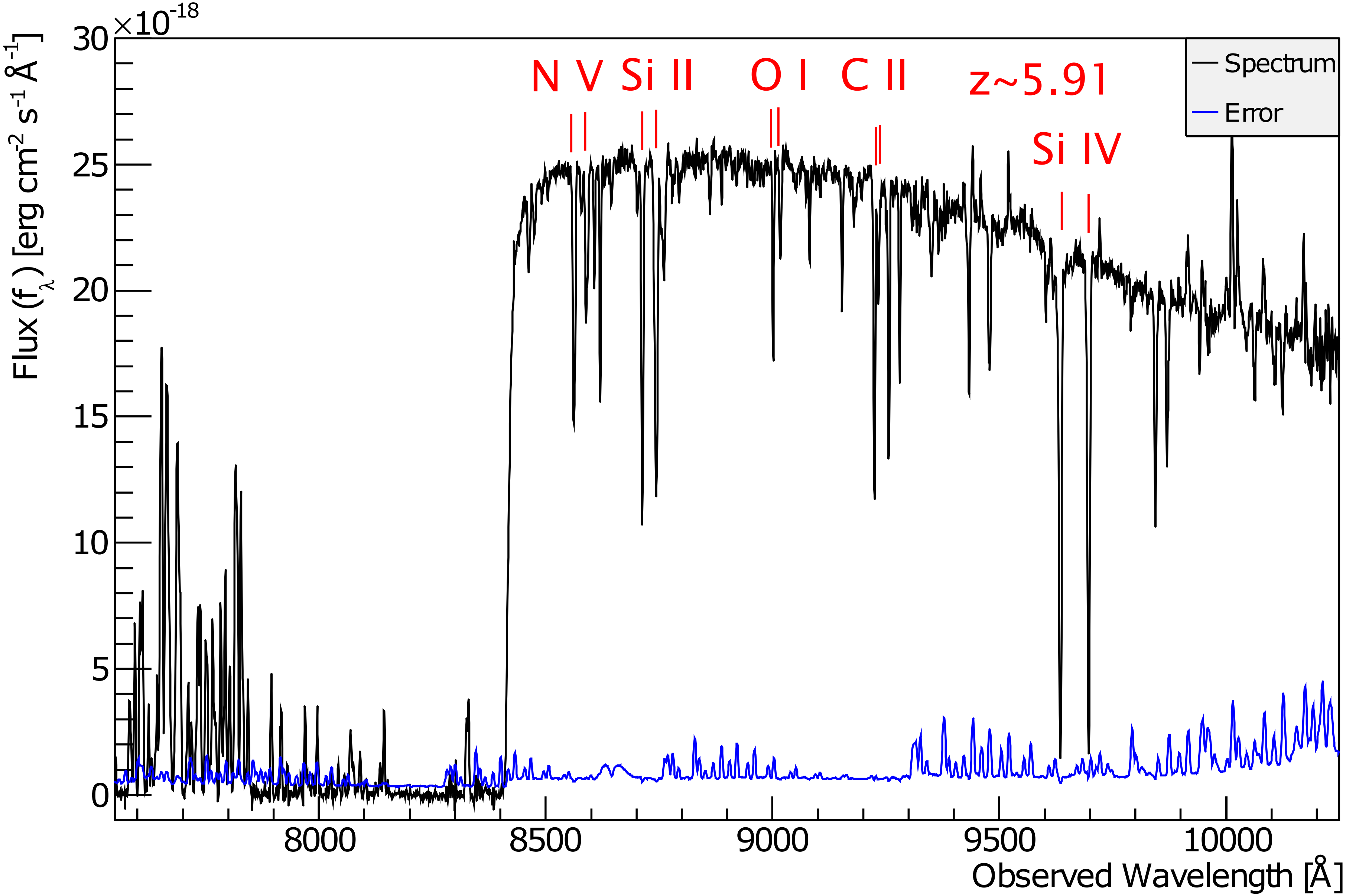
VPHグレーティング　　　グリズム



MOIRCS に搭載されたVPH-

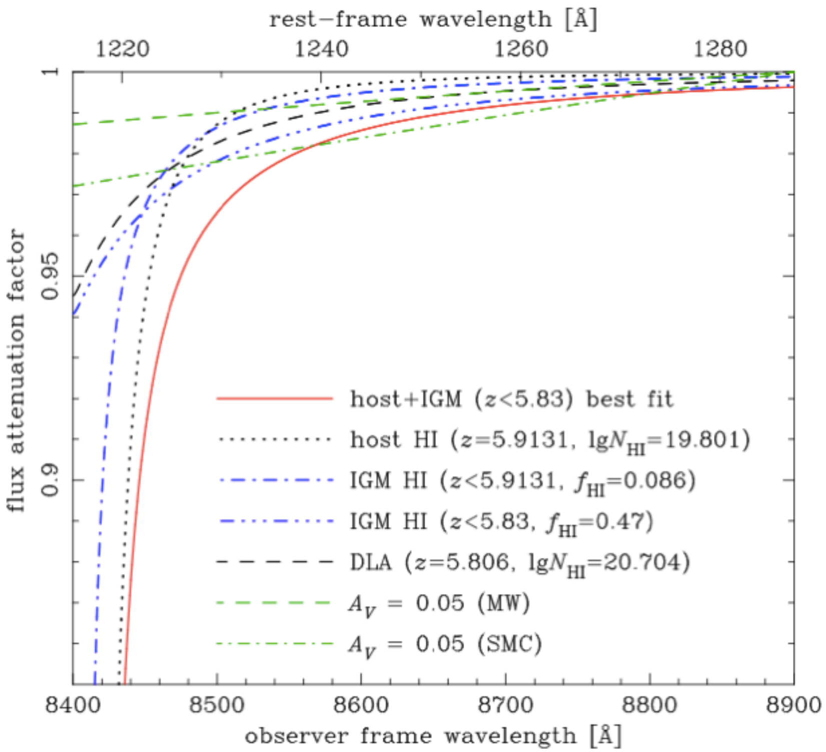
写真提供：山田、図はMOIRCS home pageより

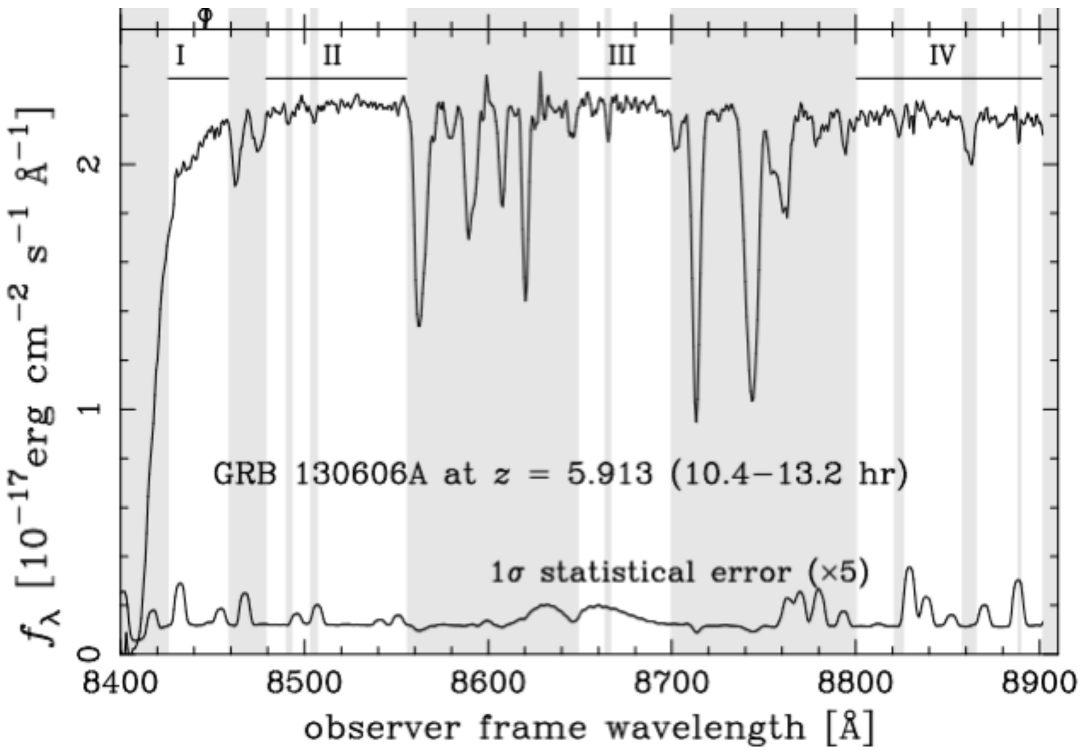
# GRB 130606A – Subaru FOCAS



# Damping Wing Analysis

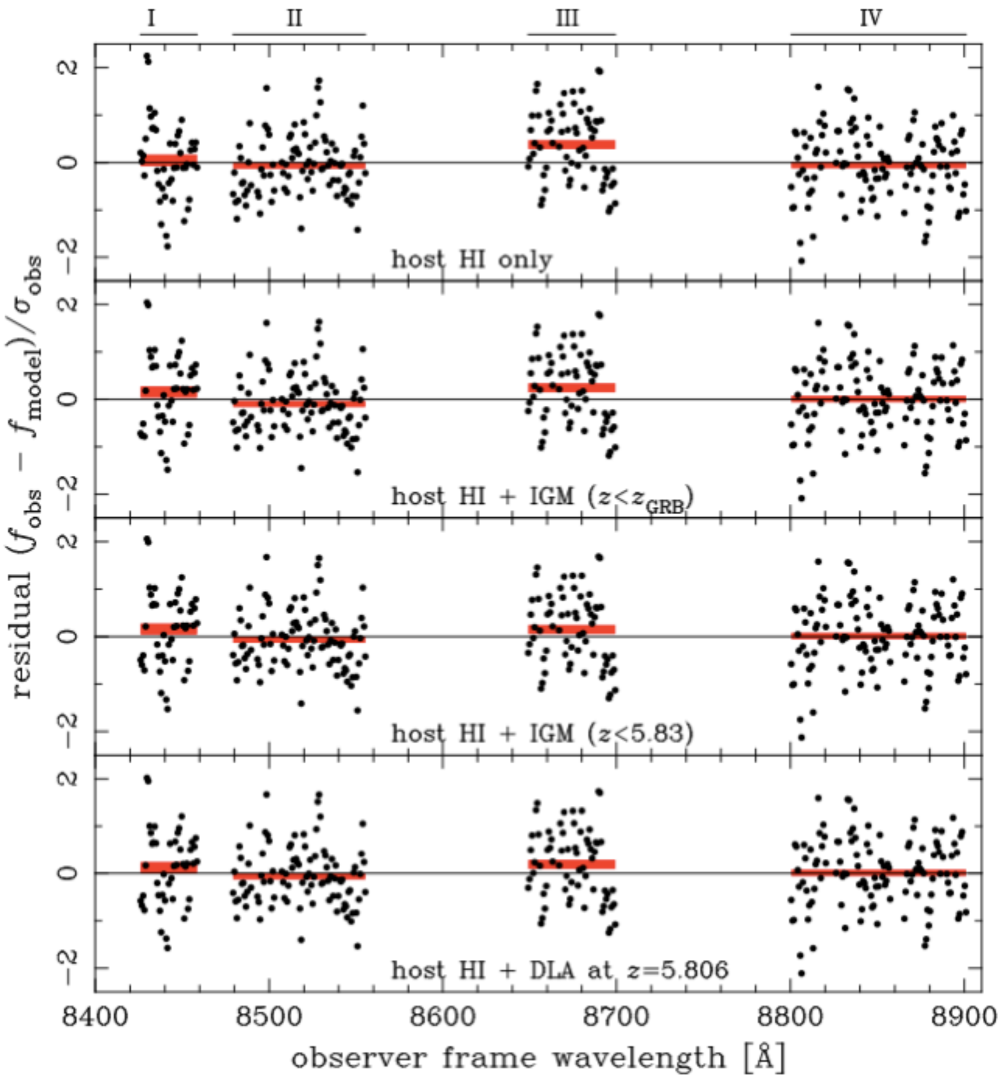
- Subaru/FOCAS spectrum in 10.4-13.2 hr after the burst
- S/N=100 per pixel (0.74A)!
- 8400-8900 A which is the most sensitive to IGM HI signature
- avoid strong absorption



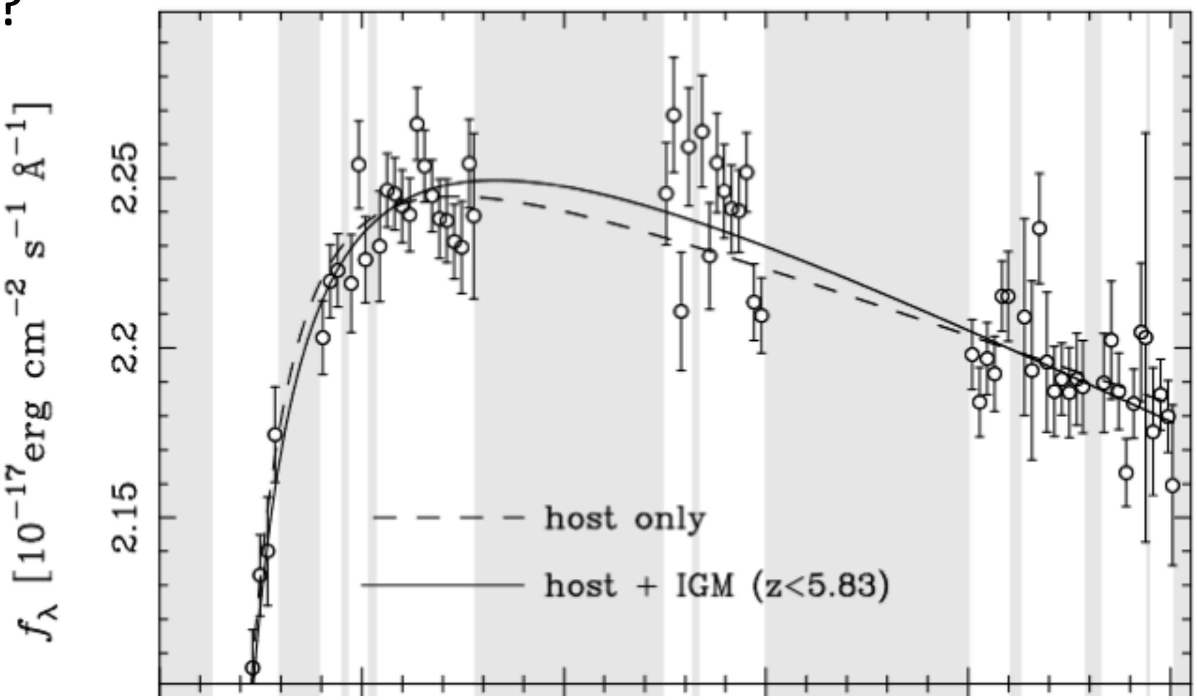



# Fitting Residuals

- power-law + host HI only
  - showing curved systematic residual
  - amplitude ~ 0.6% of continuum flux
  - 
- 3 models of intervening HI can reduce the residual by about 3 sigma statistics
  - IGM extending to $z_{GRB}$ = 5.913
  - IGM extending to $z_u$ ~ 5.8
    - corresponding to dark GP troughs to this sightline
  - a DLA at z = 5.806
    - a metal absorption system found here
    - $N_{HI}$ ~ $10^{20.7}$ $cm^{-2}$ required



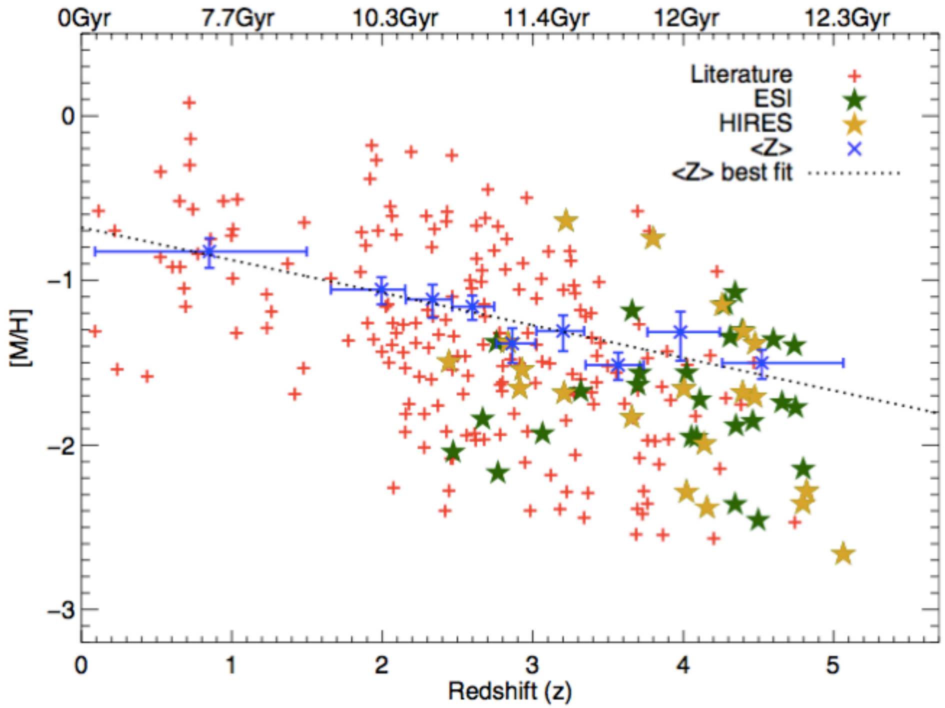
# Very subtle! systematics?




- various sources of systematics examined, but unlikely to explain the 0.6% curvature in the narrow range of 8400-8900 A
  - spectrum reduction, calibration
  - extinction at host
    - standard extinction curves do not have such a curvature
    - extinction effect should be small, from metallicity estimate
  - intrinsic curvature in aftergow spectrum?
    - too large compared with the standard afterglow theory

# diffuse IGM vs. DLA?

- the only metal absorption system at z=5.806 close to the GRB host
- if the DLA is located at this redshift,
  - $\log(N_{HI}/cm^2)$ = 20.7, much larger than in GBR host (19.7)
  - chance probability of finding such a DLA is low (~3%)
  - excluded by the profile around Lyβ feature
  - metallicity of this system must be extremely low
    - [Si/H] < -3.5 for the z=5.806 case
    - the lowest Z DLA known: -2.7
- even lower Z required if the DLA redshift is not 5.806




Rafelski+' 12

# Conclusions

- GRB 130606A gives the second opportunity to probe the re-ionization era by GRBs, next to GRB 050904

- simple power-law + host HI does not give a good fit, and intervening HI outside the host improves the fit by about 3σ
  - $n_{HI}/n_H$ ~ 0.1 if $z_{IGM,u}$ ~ $z_{GRB}$ ~ 5.913
  - $n_{HI}/n_H$ ~ 0.5 if $z_{IGM,u}$ ~ 5.8 (dark GP trough region, 5 proper Mpc away from GRB)
  - the first evidence for intervening HI to GRB sightlines

- It is difficult to make a reasonable explanation by a DLA

- diffuse IGM HI remains as a plausible explanation
  - highly neutral IGM hidden in GP trough regions?
  - indicating that the reionization not yet complete at z~6

- demonstrated the great power of GRBs to study reionization!